Saskatchewan
Ministry of
Agriculture

FINAL REPORT

RESEARCH

ADF

AGRICULTURE DEVELOPMENT FUND

20070128

OPTIMIZATION OF DDG GASIFICATION

Funded by: The Agriculture Development Fund

March 2010

Prepared by: University of Saskatchewan (U of S)

Optimization of DDG Gasification

ADF Project # 20070128

Report Submitted to:
Agricultural Development Fund
Saskatchewan Agriculture and Food

Prepared by:

T. A. Fonstad, Ph.D., P.Eng.
Department of Agricultural and Bioresource Engineering
University of Saskatchewan

Abstract:

This report covers studies to optimize the gasification of wheat dried distillers grain (DDG). DDG were gasified using oxygen-nitrogen as the gas carrier as well as with steam as the gas carrier in an attempt to improve the hydrogen and syngas production. DDG were found to have a dry heat value of approximately 26 MJ/kg and this number reduced with increasing moisture content of the feedstock. During steam gasification, both retention time and reactor temperature caused an increase in hydrogen yield. Retention time, however, showed a decrease in overall heating value as gasses such as CO were reduce with longer retention times. In contrast, reactor temperature showed an increase in syngasses and an overall increase in heating value of the produced syngas.

Growth chamber experiment examined the effect of two types of ash: dried distillers grain ash (DDGA) and meat & bone meal ash (MBMA) applied at 100 kg P ha^{-1} on canola yield and nutrient recovery on the same soil used in the field experiments. The field experiment treatments included: biochar (BC) applied alone, biochar with 50 kg N ha^{-1} (BC+N), 100 kg urea-N ha^{-1} and a control. In the growth chamber experiment the treatments were: 1 rate (100 kg P ha^{-1}) of DDGA and MBMA, 3 rates of mineral P (50, 100, 200 kg P ha^{-1}) as $Ca(H_2PO_4)_2$ and a control. All growth chamber treatments received a basal application of 200 kg N ha^{-1} as urea including the control. Biochar applied alone had limited effect on yield. However, BC+N showed equivalent yield to the urea treatment, despite having only half as much urea N added. This suggests that biochar may be improving nutrient retention and utilization. Both types of ash significantly increased yield similar to the mineral fertilizer treatment, and were deemed an effective source of phosphorus for canola nutrition.

Table of Contents

Abstract: ii
Progress to Date: iv
Recommendations iv
Administrative & Other Aspects iv
Personnel Involved: iv
Expense Statement: iv

Documents attached outlining the results of this project:

Tavasoli, A., M.G. Ahangari, C. Soni and A.J. Dalai. 2009. Production of hydrogen and syngas via gasification of the corn and wheat dry distiller grains (DDGS) in a fixed bed reactor. Fuel Process Technology 90 (2009) 472-482.

Soni, C., T.A. Fonstad, A.K. Dalai and E. Gusta. 2010. Steam Gasification of Wheat Distiller's Grains In a Fixed Bed Reactor System. Draft paper format in Optimization of DDG gasification, ADF Final Report 20070128, March 2010.

Alotaibi, K., J.J. Schoenau and T.A. Fonstad. 2010. Biochars and ashes produced from pyrolysis and gasification as amendments to increase the fertility of a Brown Chernozem soil. Paper abstract submitted for publication in the Proceedings of the Canadian Society of Soil Science Meeting, May 31 to June 4, 2010. Ottawa, Ontario.

Progress to Date:

This project was completed through employment of various post-docs, graduate students and research engineers. The initial work was to benchmark DDG gasification using air or an oxygen-nitrogen mixture (Tavasoli et al. 2009). From this work we progressed to steam gasification to investigate the use of the water in the process as the oxygen source for the combustion process and the increase in hydrogen in the syngas left over from the steam. Additionally, we cooperated with Dr. Jeff Schoenau to complete laboratory and field studies to determine the benefit of using ash from DDG and meat and bone meal (MBM) gasification.

Recommendations

Gasification of DDG has been shown to produce significant amounts of syngas using oxygen-nitrogen as the carrier gas (0.2 to 0.4 m^3/kg of biomass) and using steam as the source of oxygen and the carrier gas (0.3 to 0.6 m3/kg of biomass). Experiments using oxygen-nitrogen as the carrier gas produced a gas mixture with a heating value ranging from 9,000 kJ/kg to 12,000 kJ/kg depending on retention time and reaction temperature (Tavasoli et al. 2009). Similarly, Soni et al. (2010) reported lower heating values of the gas produced from steam gasification in the range of 5,000 kJ/kg to 11,000 kJ/kg depending on retention time and reactor temperature with reactor temperature having the most impact as higher temperature produced more gas with significantly higher heating values. These differences are the result of the changes in the composition of the syngas as process parameters are changed as the syngas is composed on hydrogen, carbon monoxide, methane, carbon dioxide and several higher carbon gasses, such as ethane and ethylene, that are broken down at the higher reaction temperatures.

Both studies showed that gasification of DDG is likely best accomplished at higher temperatures (850C to 900C) using retention times of 30 to 40 minutes.

Gasification experiments using varying moisture contents of DDG showed that the gas quantity produces increase with the moisture content of the grain but that moisture contents above 20% produced gas with a lower heating value. Gas volume increased by a factor of three while gas heating value was decreased by 30% indicating that it may be possible to economically gasify DDG as moisture contents up to 60%. More work should be done in this area as it presents possibilities to gasify DG without drying.

Additionally, the work by Alotaibi et al. 2010 has shown that biochar applied alone had limited effect on yield. However, biochar plus nitrogen showed equivalent yield to the urea treatment, despite having only half as much urea N added. This suggests that biochar may be improving nutrient retention and utilization. The ash significantly increased yield similar to the mineral fertilizer treatment, and was deemed an effective source of phosphorus for canola nutrition.

Administrative & Other Aspects

Personnel Involved:

Dr. T.A. Fonstad – Investigator
Dr. A.K. Dalia – Investigator
Dr. J.J. Schoenau – Investigator
Dr. Ahmad Tavasoli – Post Doctoral Fellow
Chirayu Soni – M.Sc. candidate in Chemical Engineering
Khaled Alotaibi – Ph.D. candidate in Soil Science
Louis Roth – Technician in Engineering
Elizabeth Gusta – Research Engineering in Chemical Engineering
William Campbell – M.Sc. candidate in Agricultural and Bioresource Engineering

Expense Statement:

Supplied by the University of Saskatchewan Financial Service Division

Fuel Processing Technology 90 (2009) 472–482

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Production of hydrogen and syngas via gasification of the corn and wheat dry distiller grains (DDGS) in a fixed-bed micro reactor

Ahmad Tavasoli [a,b], Masoumeh G. Ahangari [a,b], Chirayu Soni [a], Ajay K. Dalai [a,*]

[a] Catalysis & Chemical Reaction Engineering Laboratories, Department of Chemical Engineering, University of Saskatchewan, Saskatoon, SK, Canada S7N5C5
[b] Research Institute of Petroleum Industry, P.O. Box 14665-1998, Tehran, Iran

ARTICLE INFO

Article history:
Received 14 October 2008
Received in revised form 26 January 2009
Accepted 1 February 2009

Keywords:
Gasification
Biomass
Corn
Wheat
Dry distiller grain
Syngas

ABSTRACT

Production of hydrogen and syngas via gasification of the corn and wheat dry distiller grains (DDGS) with oxygen in a continuous downflow fixed bed micro reactor are studied in this paper. A series of experiments have been performed to investigate the effects of reaction time (15–45 min), reactor temperature (700–900 °C) and oxygen to nitrogen ratio (0.08–0.2 vol./vol.) on product gas composition, gas yield, low heating value (LHV) and carbon conversion efficiency. Over the ranges of the experimental conditions used, the results obtained seemed to suggest that for both biomasses the operating conditions were optimized for a gasification temperature around 900 °C, an oxygen to nitrogen ratio of 0.08 and a reaction time of 30 min, because a gas richer in hydrogen and carbon monoxide and poorer in carbon dioxide and hydrocarbons. The results showed that the product gas of corn DDGS gasification has higher H_2 and CO concentrations (11 and 56.5%) than that of wheat DDGS gasification (10.5 and 51.5%). In addition gasification of corn DDGS resulted to higher gas yield (0.42 m^3/kg), LHV (10.65 MJ/m^3) and carbon conversion efficiency (44.2%).

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Considering the fact that energy consumption is increasing and limited fossil fuels are nearly exhausted, with increasing populations and economic developments, renewable energy should be widely explored to renovate the energy sources structure and keep sustainable development safe. Having no/trace amount of sulphur, nitrogen, and ash, biomass is a clean alternative source and can be an excellent substitute for conventional fuels. Renewable fuels are cleaner fuels compared to traditional petroleum and coal, which reduce air pollution and lower greenhouse gas emissions. The Government of Canada recently announced a regulation requiring a 5% average renewable content, such as ethanol, in Canadian gasoline by 2010. To meet the requirements of the proposed regulations, over 2 billion liters of renewable fuels will be required, creating tremendous business opportunities for Canadian renewable fuel and agricultural producers [1]. Ethanol is a clean-burning fuel made from plants, grains or other plant and animal materials known as biomass. Unlike petroleum-based gasoline derived from the limited supply of fossil fuels under the Earth's surface, ethanol is a renewable source of energy.

By using a blend of gasoline and ethanol rather than traditional gasoline alone, motorists can help to reduce greenhouse gas (GHG) emissions and reduce global warming. In fact, it is estimated that a 5% renewable fuel standard in Canada would result in an annual 4.2 Mtons reduction in net GHG emissions — the equivalent of removing more than one million cars from Canadian roads [1]. Based on average plant sizes, there should be about 15 to 20 ethanol plants built across Canada [1]. It is known that currently Canadian firms are producing about 1 billion liters per year which should increase to 2 billion liters of ethanol per year, to meet this new standard using domestic sources [1]. One ton of grains contributes to the production of about 370–380 l of ethanol, plus valuable co-products such as about 630–640 lb of high-protein corn and wheat DDGS [1]. Currently these DDGS are used as livestock feed. Increasing the ethanol production to 2 billion liters or more, will increase the production of DDGS in such away that will exceed the need to DDGS as livestock feed. Transportation of DDGS to distant locations for utilization is expensive. Conversion of DDGS to generate energy in the plant sites seems to be logically viable for utilizing these biomasses.

There are several methods of utilizing biomass to generate energy and fuels, however, gasification processes offer technologically more attractive options for medium and large scale applications and is a more friendly way for using biomass for energy purposes, since due to the presence of non-oxidation conditions, the pollutant emissions are much lower [2–13]. Lv et al. [4] studied the air–steam gasification of pine sawdust biomass in a fluidized bed reactor. They obtained a fuel gas with the yield of 1.43–2.57 Nm^3/kg biomass and the LHV of 6741–9143 kJ/Nm^3. They showed that higher temperatures contribute to more hydrogen production, but too high

* Corresponding author. Tel.: +1 3069664771; fax: +1 3069664777.
E-mail address: ajay.dalai@usask.ca (A.K. Dalai).

0378-3820/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.fuproc.2009.02.001

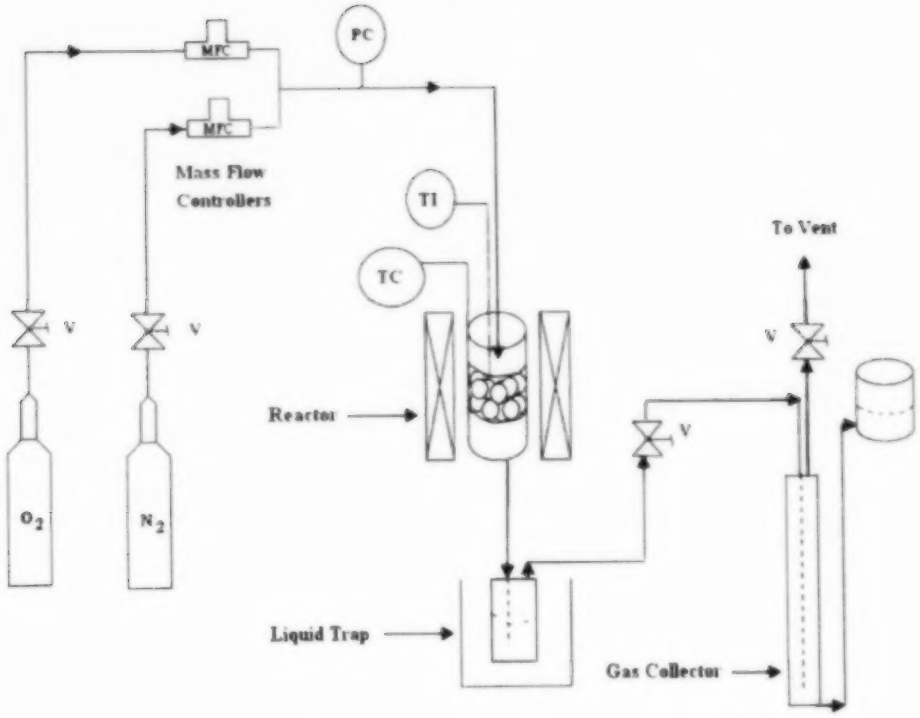


Fig. 1. Experimental set up for gasification of biomasses.

temperature lowers the gas heating value. They also stated that a smaller biomass particle is more favorable for higher gas LHV and yield. Franco et al. [5] studied the steam gasification of biomass of forestry origin (pine, eucalyptus and oak wood waste). They produced a gaseous fuel with a medium calorific value which could be employed in many end-use applications. Xiao et al. [8] studied the air gasification of polypropylene plastic waste in a fluidized bed gasifier. They showed that the fluidized bed gasification of polypropylene with air could produce a fuel gas with a calorific value in the range of 5.2–11.4 MJ/N m^3.

Hanaoka et al. [9] studied the effect of woody biomass components on air–steam gasification. They showed that the gasification conversions in cellulose, xylan, and lignin were 97.9%, 92.2%, and 52.8% on a carbon basis, respectively. The product gas composition in cellulose was 35.5 mol% CO, 27.0 mol% CO_2, and 28.7 mol% H_2, and the CO composition was higher than the CO_2 or H_2 compositions which were similar to that in the Japanese oak, of which the main component was cellulose. In contrast, the product gas compositions in xylan and lignin were approximately 25 mol% CO, 36 mol% CO_2, and 32 mol% H_2, and the CO composition was lower than the CO_2 or H_2 compositions, which were similar to those in Japanese red pine bark, of which the main component was lignin. These results suggest that the final composition of the product gas and the final heating value of the product gas are dependent to the fraction of the main components such as cellulose, hemi-cellulose, and lignin in the biomass.

Substantial research on biomass gasification has been performed during the past two decades, employing different gasifier configurations, oxidants, and modes of heating [2–13]. However, most of the biomass gasification studies performed to date have focused on the production of direct-combustion gases, not on the production of hydrogen and synthesis gas (H_2 and CO) for subsequent use as an attractive feedstock for super-clean liquid fuels and chemical synthesis.

The corn and wheat DDGS are complex oxygenated hydrocarbons and have a high potential to produce hydrogen, syngas (H_2 + CO) and hydrocarbons using processes such as pyrolysis, gasification and catalytic reforming reaction. Hydrogen is mostly used in refinery hydrotreating operations, for ammonia production and in fuel cells [14]. When these biomasses are gasified at high temperature to produce hydrogen, it is possible to obtain carbon monoxide as one of the gaseous products. Syngas is a suitable feedstock for Fischer–Tropsch synthesis to produce green diesel (long chain hydrocarbons) with high cetane number [15,16]. Synthesis gas could also make an important contribution to chemical synthesis through conversion to methanol. Alternatively, gases which are expected to be produced from thermal cracking of corn and wheat DDGS would have considerable heating value and can be used as a fuel gas to produce electricity.

Moreover, no experimental research has been performed to analyze the use of these low value corn and wheat DDGS into energy, conventional liquid fuels and value-added products. The present work reports results of initial corn and wheat DDGS gasification tests over a range of reaction times, reactor temperatures and oxygen to nitrogen ratios. Particular emphasis is given to measure the hydrogen and carbon monoxide yields and the dry product gas low heating value (LHV) with the overall goal of optimizing the conversion of these biomasses into hydrogen and synthesis gas.

2. Methods

2.1. Feed materials

The biomass particles used for the experiments were DDGS of corn and wheat. The corn DDGS was obtained from ADM Agri-Industries Company, Inc. located at Owensboro, KY, USA and the wheat DDGS

Table 1
CHNS analysis of biomass species

Biomass	Corn dried distiller grains	Wheat dried distiller grains
N	4.6	5.1
C	45.5	45.1
H	7.2	7.0
S	0.8	0.3
O	41.6	42.5

was obtained from NorAmera Bioenergy ethanol plant located at Weyburn, SK, Canada.

2.2. Reaction setup and experimental outline

Biomass gasification was carried out in a continuous down flow fixed bed micro reactor made of Inconel 600 alloy under atmospheric pressure (see Fig. 1). The experiments were performed with biomass in powder form. The reactor was 500 mm long with 10.5 mm internal diameter and was filled with 0.75 g of powdered biomass. The biomass sample was held on a plug of quartz wool, which was placed on a supporting mesh (a three way vane) at the center of reactor. The temp ⁻ of the reactor was measured and controlled using K-type thermocouple placed at the heating zone in the furnace and connected to temperature controller (Shimaden SR22, Tokyo, Japan). Another K-type thermocouple (using thermo well) was placed inside the bed to measure the bed temperature. N_2 and O_2 were fed into the reactor at the desired flow rates using separate mass flow controllers while the reactor temperature reached 100 °C. It took approximately 20–30 min to achieve the desired operating temperature. The runs were continued for another 15–45 min at the desired temperature to complete the reaction.

The product leaving the reactor was condensed and separated into liquid and gaseous fractions. The liquid product fraction was collected in a liquid trap, cooled with ice-salt bath and the gaseous product was collected over a saturated brine solution of sodium chloride. The reactor was then cooled and weighed to determine the amount of char. The volume of gas was measured at standard temperature of 25 °C and 1 atm pressure. A Hewlett Packard (HP) 5890 gas chromatograph (GC) equipped with the thermal conductivity detector (TCD) having Carbosive S II column (3 m, i.d. 3.18 mm) was used to analyze H_2, CO and CO_2. Hydrocarbons such as CH_4, C_2H_4, C_2H_6 and C_3+ were analyzed using a HP 5880GC, equipped with the flame ionization detector (FID) and Chromsorb 102 Column (1.8 m, i.d. 3.18 mm). Helium gas was used as a carrier gas in both the GCs.

Experiments were accomplished using corn and wheat DDGS at atmospheric pressure. Parametric gasification tests, varying reaction time (15–45 min), O_2/N_2 ratio (0.08–0.2) and temperature (700–900 °C) were performed. At the end of each run the volume of produced gas was measured, the volumetric percentage of H_2, CO, CO_2 and hydrocarbons were determined and the amount of carbon converted to dry gas were calculated. In addition, three important indices of gasification performance including carbon conversion efficiency (η_c), dry heating value (LHV) and gas yield per unit mass of biomass (GY) were computed. Also pyrolysis of corn and wheat DDGS were carried out at 900 °C and the results were compared with those of gasification of corn and wheat DDGS at 900 °C.

3. Results and discussion

The CHNS analyses of the biomasses are given in Table 1. As indicated, the C and H contents in these materials are between 52 and 53%. The balance is mostly oxygen.

3.1. Effect of reaction time

In order to determine the time required for complete conversion of these biomasses, the effects of reaction time on biomass conversion and product gas composition have been studied at reaction temperature of 850 °C and O_2/N_2 volumetric ratio of 0.08. Reaction time is varied in this test system by increasing the duration of gasification process after the temperature of the reactor reaches its maximum while fixing the oxygen and nitrogen flow.

The inert-free gas compositions for corn DDGS biomass as a function of reaction time are shown in Table 2. It is to note that all data in this table were repeated for 3 times and due to uniformity of the biomass, the results of all the 3 runs were completely similar. The trends presented in this table show that for corn DDGS biomass the net amount of each product gas increases with increasing the reaction time and reaches a maximum at reaction time of 30 min at which complete carbon conversion is achieved. However, it shows that increase in reaction time increases the percentage of CO significantly, increases the percentage of CO_2 partly, and decreases the percentage of H_2 in the final product gas mixture indicating that H_2 is a primary product during gasification of corn dried distiller grains. Also Table 2 shows that the percentage of CH_4 and higher hydrocarbons (C_2+) in the final product gas mixture decreases with increasing the reaction time. It is generally referred by different authors that the process of biomass gasification occurs through three steps [8]. First, a large amount of gas is produced in the initial pyrolysis at high bed temperatures. Second, the high temperature favors the tar cracking reactions, producing more light hydrocarbons and other gas phase products (CO, CO_2 and H_2). Third, char gasification is enhanced by the Boudouard reaction. The gasification mechanism of corn DDGS biomass particles might be described by the following reactions:

$$\text{Corn dried distiller grains} \longrightarrow \text{Gas} + \text{Tars} + \text{Char} \quad (1)$$

$$\text{Tars} \longrightarrow \text{Light and heavy hydrocarbons} + \text{CO} + \text{CO}_2 + \text{H}_2 \quad (2)$$

$$\text{Heavy hydrocarbons} \longrightarrow \text{Light hydrocarbons} + \text{H}_2 \quad (3)$$

$$\text{Char} \longrightarrow \text{CO} + \text{CO}_2 + \text{H}_2 + \text{Solid residual} \quad (4)$$

The final product gas composition of the biomass gasification process is the result of combination of the above mentioned series of complex and competing reactions. The formation of CO and CO_2

Table 2
The inert-free gas compositions for corn dried distiller grains biomass as a function of reaction time (T = 850 °C and O_2/N_2 ratio = 0.08)

Time (min)	15		20		25		30		45	
	Vol. (ml)	%	Vol. (ml)	%	Vol. (ml)	%	Vol. (ml)	%	Vol. (ml)	%
CH_4	13.4	9.97	13.54	5.4	13.58	4.78	13.64	4.52	13.7	4.48
C_nH_m	4.3	3.20	4.51	1.8	4.56	1.61	4.6	1.51	4.6	1.50
H_2	19.8	14.72	27.08	10.80	29.16	10.27	30.2	10.05	30.3	9.88
CO	61.1	45.44	134.12	53.48	154.97	54.57	165.4	55.03	170.3	55.56
CO_2	35.9	26.67	71.52	28.52	81.71	28.77	86.8	28.87	87.6	28.58

Table 3
The inert-free gas compositions for wheat dried distiller grains biomass as a function of reaction time ($T = 850$ °C and O_2/N_2 ratio = 0.68).

Time (min)	15		20		25		30		45	
	Vol. (ml)	%	Vol. (ml)	%	Vol. (ml)	%	Vol. (ml)	%	Vol. (ml)	%
CH_4	12.3	9.74	14.54	6.03	15.18	5.55	15.5	5.32	15.6	5.31
C_nH_m	2.7	2.10	4.18	1.73	4.59	1.68	4.8	1.66	4.84	1.65
H_2	16.9	13.44	25.46	10.55	27.89	10.18	29.2	10.01	29.3	10.00
CO	55.2	43.78	118.88	49.29	136.81	49.98	146.9	50.28	147.5	50.35
CO_2	38.9	30.87	78.13	32.39	89.29	32.62	95.6	32.73	95.7	32.68

through the final step of the gasification (Eq. (4)) can be studied via the reactions, given below, occurring to a varying degree [8,17].

Oxidation:

$$C + O_2 \longrightarrow CO_2 \tag{5}$$

$$C + 1/2\,O_2 \longrightarrow CO \tag{6}$$

Boudouard:

$$C + CO_2 \longrightarrow 2CO \tag{7}$$

It has been shown that the reaction of carbon (C) with CO_2 (Eq. (7)) is independent of the quantity of char (C) and is zero order with respect to carbon for considerable extent of reaction, while the rate of reaction of carbon (C) with oxygen (Eqs. (5) and (6)) declines as the carbon is deleted and is approximately first order with respect to carbon [17]. The results of our experiments showed that by increasing the reaction time from 15 to 30 min the amount of char produced in the reactor is decreased from 0.13 g to 0.04 g indicating that the average amount of carbon participating in the reactions (5)–(7) decreases with increasing the reaction time. This shows the importance of reaction (7) during the last periods of the reaction by which, most of the produced carbon dioxide reacts with carbon to produce CO and this could explain significant improvement on CO percentage in contrast to partly increase in CO_2 percentage in the product gas by increasing the reaction time.

The inert-free gas compositions for wheat DDGS biomass as a function of reaction time are shown in Table 3. The trends are quite similar to that of the corn DDGS. However the total volumes of H_2 and CO gases produced during wheat DDGS gasification process are a little lower than that of corn DDGS (See Tables 2 and 3) which could be due to higher H and C content of corn DDGS in comparison to wheat dried distiller grains. The DDGS with lower percentage of lignin and higher percentage of cellulose are better for production of H_2 and CO. Corn DDGS have more cellulose and lower lignin than the wheat DDGS [1,9]. This can be another reason for higher volumes of H_2 and CO gases produced during corn DDGS gasification process. In addition the ratio of CO/CO_2 in the product gas of corn DDGS is 1.90 while that for wheat DDGS is 1.54 which indicates that the corn DDGS is a better biomass for syngas production purposes.

The influences of reaction time on gasification performance are presented in Figs. 2 and 3. In these figures GY is volume of dry inert-free gas produced per unit mass of the biomass, and the carbon conversion efficiency (η_c) and dry heating value (LHV) of the product gas are calculated as follows [4]:

$$\mathrm{LHV} = (30.0 \times \mathrm{CO} + 25.7 \times \mathrm{H_2} + 85.4 \times \mathrm{CH_4} + 151.3 \times \mathrm{C_nH_m}) \times 4.2\,(\mathrm{kJ/Nm^3}) \tag{8}$$

Where CO, H_2, etc. are the gas concentrations of the product gas.

$$\eta_c = \frac{V_g \times 1000\,(\mathrm{CH_4\%} + \mathrm{CO\%} + \mathrm{CO_2\%} + 2\,(\mathrm{C_2H_2\%} + \mathrm{C_2H_4\%}) + 3\,(\mathrm{C_3H_6\%} + \mathrm{C_3H_8\%}) + \ldots) \times 12.224}{W \times C\%} \times 100 \tag{9}$$

Where $CH_4\%$, CO% (vol.%), etc. are the gas concentration and V_g (Nm^3) is the dry product gas volume. C_nH_m is hydrocarbons heavier than methane. W is the weight of biomass and C% is the carbon

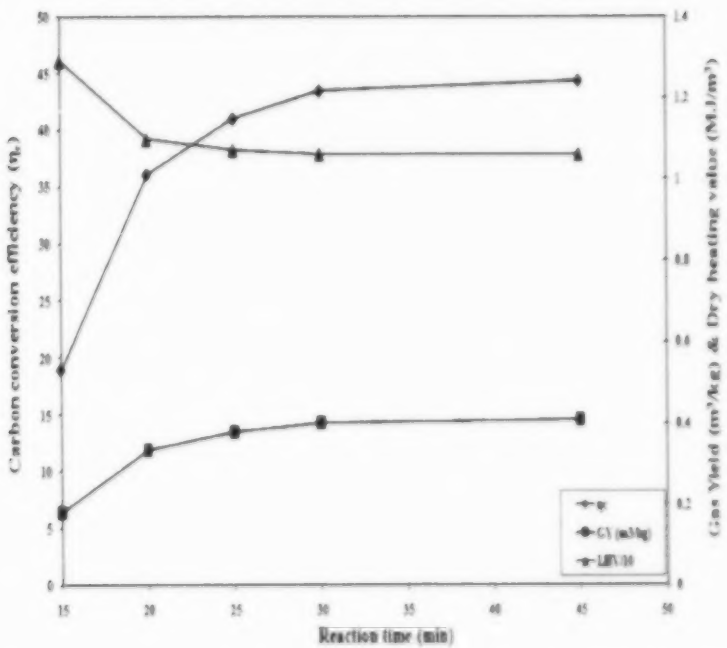


Fig. 2. Influences of reaction time on carbon conversion efficiency, gas yield and dry heating value for gasification of corn dried distiller grains ($T = 850$ °C and $O_2/N_2 = 0.68$).

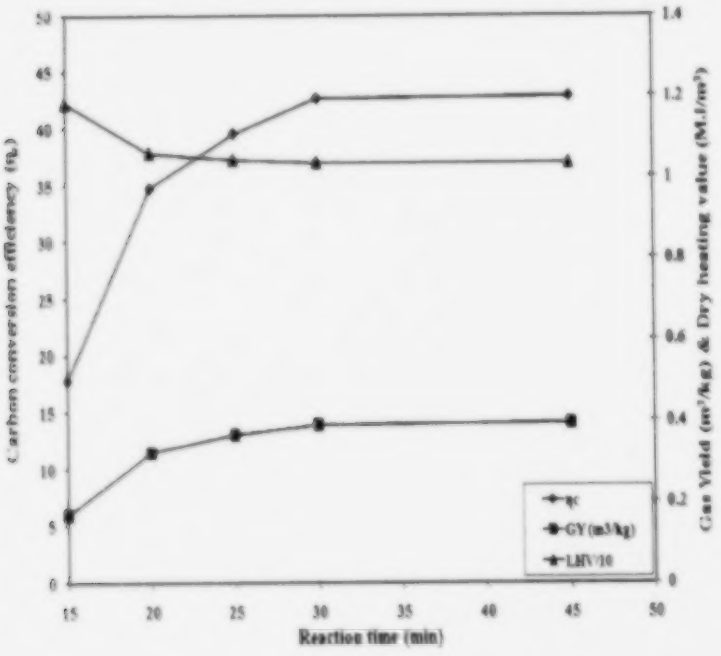


Fig. 3. Influences of reaction time on carbon conversion efficiency, gas yield and dry heating value for gasification of wheat dried distiller grains ($T = 850$ °C and $O_2/N_2 = 0.08$).

content in the ultimate analysis of biomass. The trends in Figs. 2 and 3 show that for both biomasses carbon conversion efficiency and gas yield increase with increasing the reaction time, reach a maximum at reaction time of 30 min at which complete carbon conversion is achieved. Comparison of the data shows that in the case of corn DDGS the amounts of carbon efficiency, gas yield, and the dry heating value of the product gases are slightly higher than those for wheat dried distiller grains. These figures also show that for both biomasses in contrast to the carbon conversion efficiency and gas yield, the dry heating value of the product gases decreases with increasing the reaction time. However it reaches it's minimum value at reaction time of 30 min and remains approximately constant afterwards. The decreases of dry heating values with increasing reaction time are due to decrease in the concentrations of methane and other light

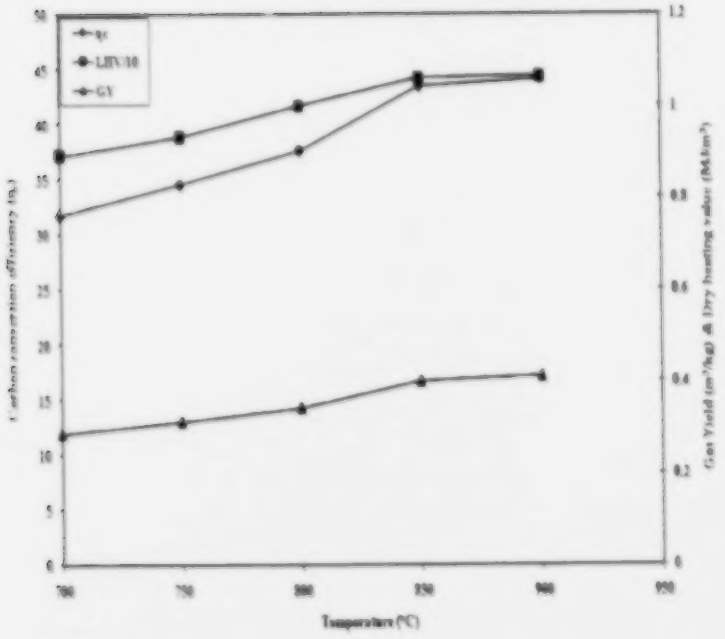


Fig. 4. Influences of temperature on carbon conversion efficiency, gas yield and dry heating value for gasification of wheat dried distiller grains (reaction time = 30 min, $O_2/N_2 = 0.08$).

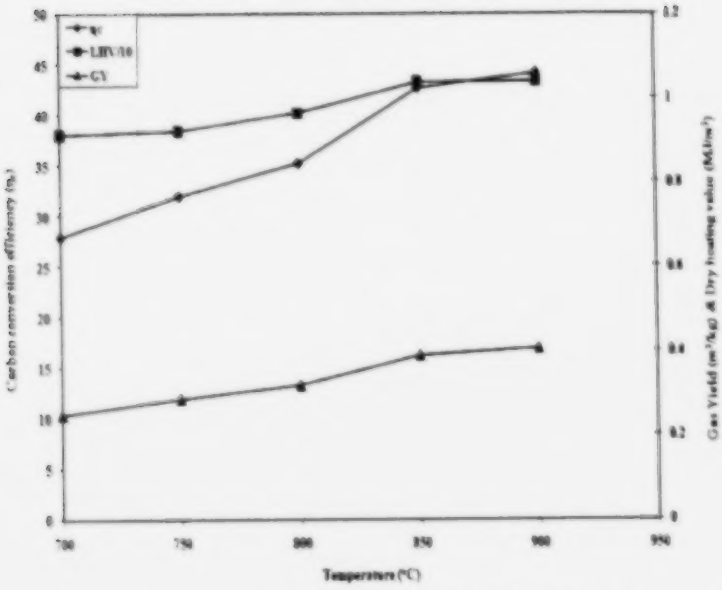


Fig. 5. Influences of temperature on carbon conversion efficiency, gas yield and dry heating value for gasification of wheat dried distiller grains (reaction time = 30 min, $O_2/N_2 = 0.08$).

hydrocarbons which have relatively large heating values and also due to increased formation of carbon dioxide.

The results obtained seem to suggest that the optimized reaction time for gasification temperature for corn and wheat DDGS could be 30 min, because the gas obtained has higher content of hydrogen and CO and low contents of hydrocarbons and CO_2. This reaction time would also favor energy and carbon conversions, as well as gas yield (see Figs. 2 and 3).

3.2. Effect of temperature

Temperature is crucial for the overall biomass gasification process. In order to find the suitable gasification temperature, the effects of temperature on gasification product yields for the two biomass species have been studied. The reactor temperature was varied from 700 to 900 °C in 50 °C increments holding the O_2/N_2 ratio constant ($O_2/N_2 = 0.08$). The results of GY, LHV and η_c for both biomasses are presented in Figs. 4 and 5. As expected, in the case of both biomasses the increase in the amount of temperature led to higher gas yield. The increase in gas yield with temperature, could be due to various reasons, such as: (i) higher production of gases in the initial pyrolysis step, whose rate is faster at higher temperatures [5], (ii) the production of gas through the endothermic char gasification reactions, which are favorable at elevated temperatures and, (iii) the increase of gas yield resulting from cracking of heavier hydrocarbons and tars. Over the temperature range of 700–850 °C, the gas yield increased by 38 and 56% for corn and wheat DDGS respectively, however, by increasing the temperature to 900 °C there was slighter variation of the gas yield as a function of temperature for both types of biomass used. Also Figs. 4 and 5 show that by increasing the reaction temperature from 700 to 850 °C, the carbon conversion efficiency (η_c) increased from 31.2 to 43.5 (39.4% enhancement) and from 28 to 42.5 (51.7% enhancement). Also, by increasing the temperature to 900 °C, the efficiencies are enhanced by 1.6 and 3% in the case of corn and wheat DDGS respectively which are less significant. This, in fact, shows that the reaction of char is promoted by the rise in the temperature, as the gasification reactions are endothermic. In addition, Figs. 4 and 5 show that LHV increased for both biomasses with increasing temperature due to increasing %CO and $\%H_2$ and decreasing $\%CO_2$ (see Figs. 6 and 7). The differences on the amounts of GY and η_c for corn and wheat DDGS could be due to H and C content of the two biomasses and the variation in reactivities of chars produced during their pyrolysis step.

The effects of temperature on the gas composition for the two biomass species are shown in Figs. 6 and 7. The gas composition plotted in these figures is inert-dry-free gas. The effect of temperature on gas composition produced from corn DDGS gasification is shown in Fig. 6. The rise in temperature from 700 to 900 °C was found to increase H_2 formation from 8.9 to 11 mol% and CO formation from 32.5 to 56.5%, whilst CO_2 decreased from 49.4 to 26.4%. CH_4 and C_nH_m hydrocarbon concentrations were also observed to decrease from 7 to 4.3% and 2.1 to 1.2% respectively. The gas compositions show significant variation over the range from 700 to 850 °C however, by increasing the temperature from 850 to 900 °C the variations of the gas compositions as a function of temperature is lesser. These trends agree fairly well with the results reported by other researchers, for instance Wang and Kinoshita [2], however for different biomass species. The final gas composition of the gasification process is the result of the combination of a series of complex and competing reactions (Eqs. (1)–(7)). The decrease in the concentration of CO_2 and increase in the concentration of CO with temperature can be attributed to the reaction of CO_2 with carbon to produce CO via Boudouard reaction (Eq. (7)). According to the Le Chatelier's principle, higher temperatures favor the reactants in exothermic reactions and favor the products in endothermic reactions. The endothermic reaction in Eq. (7) ($\Delta H = 172$ kJ) was strengthened with increasing temperature, which resulted in an increase in CO concentration and a decrease in CO_2 concentration. Kinetic expressions cited in the literature [17,18] for carbon dioxide–carbon reaction predict a 200 fold increase in reaction rate over the temperature range of 200 °C. Also decreasing the concentration of CH_4 and higher hydrocarbons (C_nH_m) with increasing the reactor temperature can be attributed to the more favorable conditions for thermal cracking reactions at elevated temperatures. Cracking of the mentioned hydrocarbons in accordance with endothermal char gasification reaction (Eq. (4)) and cracking of tars (Eq. (3)) which are favorable at elevated temperatures can explain the increase in the concentration of H_2 with increasing reactor temperature.

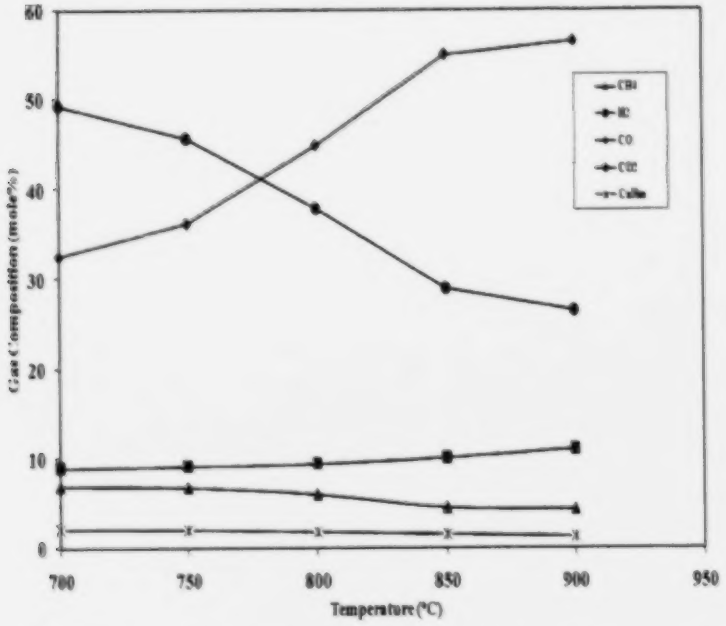


Fig. 6. Influences of temperature on product gas composition for gasification of corn dried distiller grains (reaction time = 30 min, O_2, N_2 = 0.08).

The results obtained using wheat DDGS are given in Fig. 7. Similar to the results obtained for corn DDGS, in this case, the rise in temperature from 700 to 900 °C was found to increase H_2 formation from 8.6 to 10.5 mol% and CO formation from 29.2 to 51.5%, whilst CO_2 decreased from 51.3 to 31.4%. CH_4 and C_nH_m hydrocarbon concentrations were also observed to decrease from 8.4 to 5% and 2.4 to 1.5% respectively. The values obtained for CO and H_2 are a little lower than that for corn DDGS while the concentration of CO_2 is higher, indicating better product gas for corn DDGS gasification process. In the case of corn DDGS biomass the sharp decrease in the concentration of CO_2 and increase in the concentration of CO is observed between the reactor temperatures of 750 and 850 °C, however those for wheat DDGS mainly it is observed between 800 and 850 °C. The differences could be due to the variation in reactivities of chars produced during

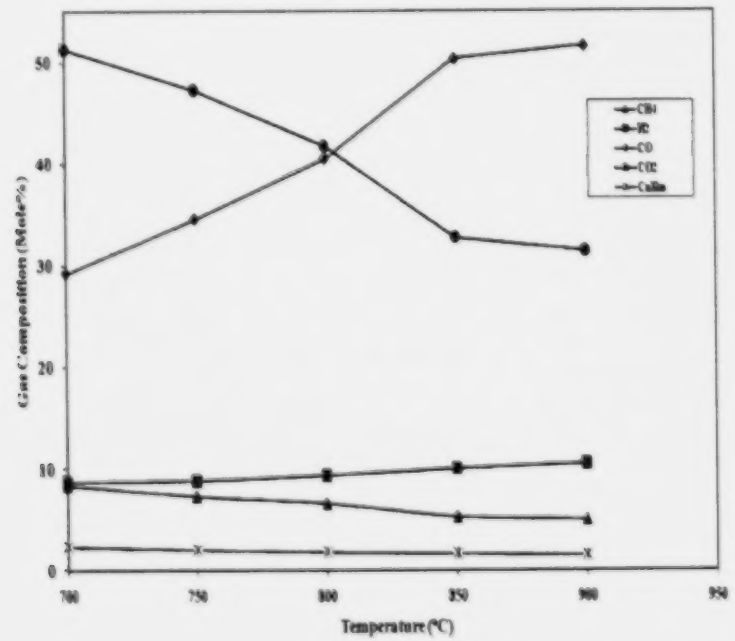


Fig. 7. Influences of temperature on product gas composition for gasification of wheat dried distiller grains (reaction time = 30 min, O_2, N_2 = 0.08).

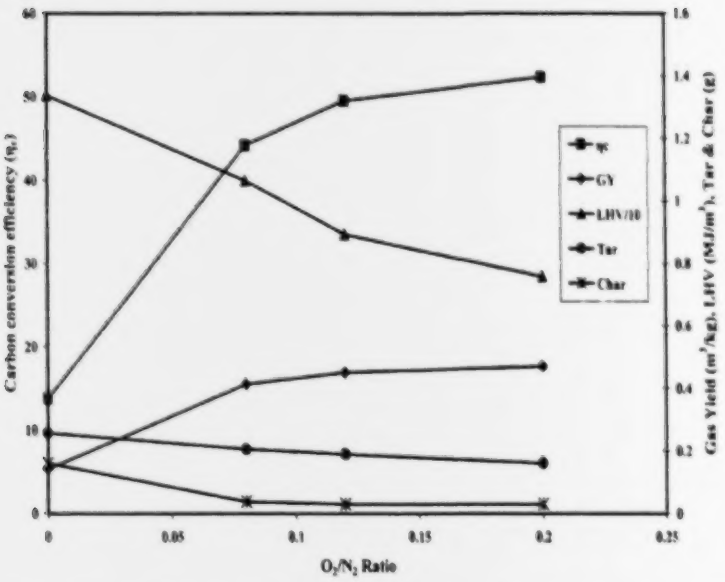


Fig. 8. Influences of O_2/N_2 ratio on carbon conversion efficiency, gas yield and dry heating value for gasification of corn dried distiller grains (reaction time = 30 min, T = 900 °C).

their pyrolysis step. Equilibrium computations predict that char disappears and the concentration of carbon monoxide and carbon dioxide change abruptly at 750 °C, and that the gas composition changes very little at temperatures above 750 °C [19]. However, such trends were not observed in these experiments. All gaseous components vary with temperatures above 750 °C indicating the existence of nonequilibrium gasification conditions.

The results obtained so far seem to suggest that the optimized gasification temperature for corn and wheat DDGS biomasses could be 900 °C or above, because the gas obtained have greater content of hydrogen, less hydrocarbons and more importantly greater CO/CO_2 ratios. This temperature would also favor energy and carbon conversions, as well as gas yield (see Figs. 4 and 5). The main disadvantage of using this higher temperature could be the high operational costs due to the need for indirect heating.

3.3. *Effect of O_2/N_2 ratio*

The results of parametric O_2/N_2 ratio tests for corn DDGS biomass are presented in Figs. 8 and 9. O_2/N_2 ratio was increased from 0.08 to 0.2 keeping other conditions constant. To compare the pyrolysis of the biomasses with the gasification using oxygen performance, two

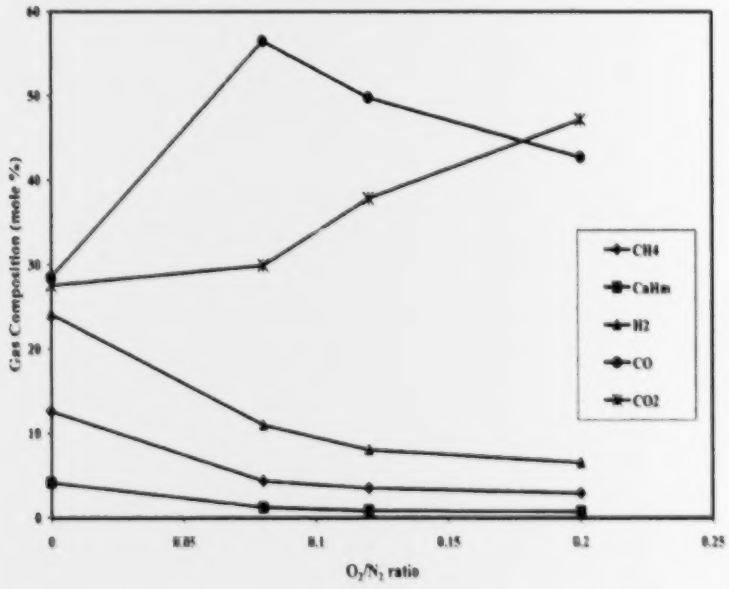


Fig. 9. Influences of O_2/N_2 ratio on product gas composition for gasification of corn dried distiller grains (reaction time = 30 min, T = 900 °C).

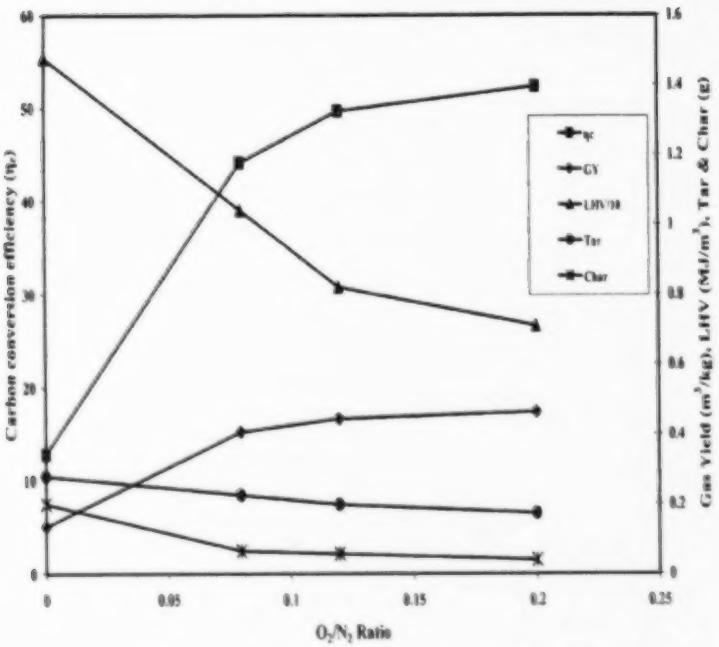


Fig. 10. Influences of O_2/N_2 ratio on carbon conversion efficiency, gas yield and dry heating value for gasification of wheat dried distiller grains (reaction time = 30 min, T = 900 °C).

pyrolysis experiments with corn and wheat at 900 °C have been performed. The results of corn DDGS pyrolysis ($O_2/N_2 = 0.0$) are added to Figs. 8 and 9. As expected, the gasification resulted in the production of a larger volume of gas than that from the pyrolysis. Also a strong influence of O_2/N_2 ratio on the product gas yield, char and tar was observed. Gas yield increased with increasing O_2/N_2 ratio. For O_2/N_2 ratios in the range of 0.0 to 0.20, the gas yield increased from 0.14 to 0.47 m^3/kg of corn DDGS, while the tars reduced from 0.26 to 0.16 g. It seems that higher partial pressure of O_2 in the reactor favors the tar cracking reactions, producing more light hydrocarbons and other gas phase products. On the other hand, char yield decreased with increasing O_2/N_2 ratio from 0.16 to 0.03 g over the range of O_2/N_2 ratio studied, indicating enhancement of char gasification with increasing O_2 partial pressure. Fig. 8 also shows that carbon conversion efficiency increases and dry product gas low heating value (LHV) decreases with increasing O_2/N_2 ratio. The decrease in LHV with increasing O_2/N_2 ratio is due to increasing CO_2 and decreasing CH_4 and C_nH_m percentage in the composition of final product gas (see Fig. 9). High O_2/N_2 ratio causes gas quality to degrade because of more oxidation reactions.

The product gas composition of corn DDGS gasification is plotted in Fig. 9 as a function of O_2/N_2 ratio. As shown, H_2, CH_4 and other light hydrocarbon concentrations decrease with increasing O_2/N_2 ratio. CO_2 concentration increased with increasing O_2/N_2 ratio, while CO concentration increased significantly with increasing O_2/N_2 ratio, passed through a maximum at O_2/N_2 ratio of 0.08 and then started to decrease. It seems that in the first stage (O_2/N_2 ratio of 0.0–0.08), reaction (6) was more likely to occur than reaction (5) because of the lack of oxygen. Reaction (5) consumes 0.5 mol more oxygen than reaction (6). Therefore, oxidation reactions of tars, char and combustible product gases became more important in the second stage (O_2/N_2 ratio of 0.08–0.20) which in turn leads to higher concentration of CO_2 and lower concentration of CO at high values of O_2/N_2 ratio [4].

The results of wheat DDGS biomass gasification at different O_2/N_2 ratio are presented in Figs. 10 and 11. Similar to the corn DDGS, gasification of wheat DDGS resulted in the production of a larger volume of gas compared to pyrolysis. The product gas yield increased up to 2 fold by increasing O_2/N_2 ratio from 0.0 to 0.08. Further increase of O_2/N_2 ratio up to 0.2 slightly increased the gas yield by 14%. Also, increasing the O_2/N_2 ratio from 0.0 to 0.2 decreased the tars from 0.28 to 0.17 g. In addition, char yield decreased from 0.20 to 0.04 g over the rage of O_2/N_2 ratio studied. It confirms that, higher partial pressures of the O_2 in the reactor favors the tars cracking and char gasification reactions. Fig. 10 also shows that carbon conversion efficiency increases significantly. In addition dry product gas low heating value (LHV) decreases by about 50% with increasing O_2/N_2 ratio from 0.0 to 0.2, which is due to increasing CO_2 and decreasing CH_4 and C_nH_m percentage in the composition of final product gas (see Fig. 11).

The product gas composition for wheat DDGS gasification as a function of O_2/N_2 ratio is plotted in Fig. 11. H_2, CH_4 and C_nH_m light hydrocarbon concentrations in the gas phase decreased from 26.3 to 5.9%, 16.1 to 2.9% and 4.6 to 0.85, respectively, over the range of increasing O_2/N_2 ratio. CO_2 concentration exhibited an opposing trend, increasing from 27.5 to 51.6%. CO concentration increased from 25.5 to 51.5% with increasing O_2/N_2 ratio from 0.0 to 0.08, passed through a maximum at O_2/N_2 ratio of 0.08 and then decreased to 38.8% at O_2/N_2 ratio of 0.2. Similar to the results of Corn DDGS biomass, it shows that, oxidation reactions of tars, char and combustible product gases became more dominant at higher O_2/N_2 ratios.

The ratio of CO/CO_2 is an important parameter for the gasification of biomass to produce syngas. Fig. 12 presents the results of CO/CO_2 ratios for both biomasses at different values of O_2/N_2 ratio. It shows that corn DDGS gasification leads to higher amount of CO and lower amounts of CO_2 than wheat DDGS gasification. The differences could be due to the variation in the reactivities of chars produced during their pyrolysis step.

Through the analysis on the experimental data of varying O_2/N_2 ratio, it can be understood that it is unfeasible to apply too small or too large O_2/N_2 ratio in corn and wheat DDGS biomasses gasification to produce H_2 and syngas. Too small O_2/N_2 ratio will lower the total product gas and too large O_2/N_2 ratio will consume more H_2 and other combustible gases through oxidization reaction and decrease

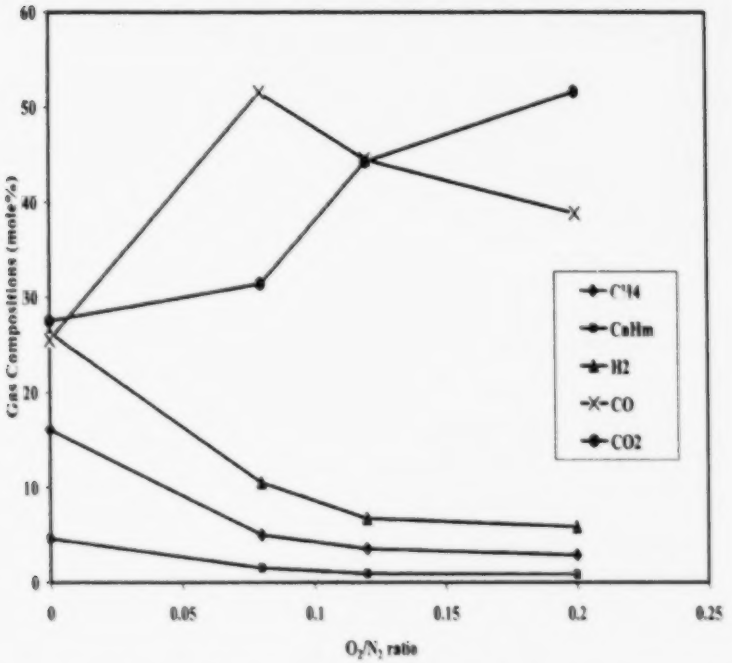


Fig. 11. Influences of O_2/N_2 ratio on product gas composition for gasification of wheat dried distiller grains (reaction time = 30 min, T = 900 °C).

the CO/CO_2 ratio. So there exists an optimal value for O_2/N_2 ratio, which can be different for different biomasses. In the present study, the optimal value of O_2/N_2 ratio was found to be 0.08 for both corn and wheat DDGS biomasses. It is to note that due to low value of O_2/N_2 ratio, the final product has a high content of nitrogen (about 40–60%). The desired products must be separated from the final product gas by using different techniques like pressure swing adsorption (PSA). However, the reactor that is used in this study was a fixed bed micro-reactor and the industrial biomass gasification reactors are fluidized bed reactors which have different conditions and the amount of nitrogen in the final product gas will not be as much as the nitrogen that is used in this study.

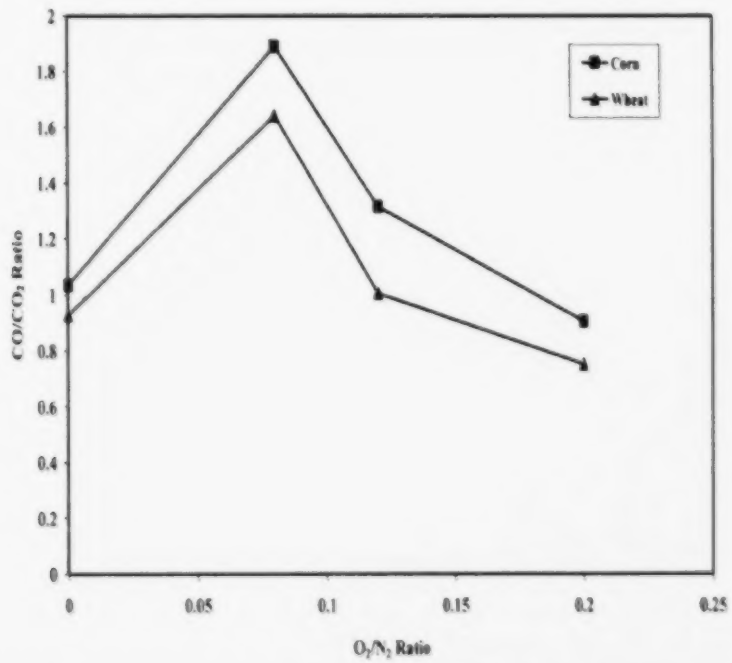


Fig. 12. Influences of O_2/N_2 ratio on CO/CO2 ratio for gasification of corn dried distiller grains and wheat (reaction time = 30 min, T = 900 °C).

4. Conclusions

Gasification of corn and wheat DDGS were successfully carried out, producing a gas with considerable H_2 and CO concentrations and a medium calorific value, which could be employed in many end-use applications. For both biomasses the operating conditions were optimized for a gasification temperature around 900 °C, an oxygen to nitrogen ratio of 0.08 and a reaction time of 30 min, due to the production of a gas richer in hydrogen and carbon monoxide and poorer in carbon dioxide and hydrocarbons. The product gas of corn DDGS gasification has higher H_2 and CO concentrations and lower concentration of CO_2 than that of wheat DDGS gasification. Gasification of corn DDGS results in higher gas yield, higher dry product gas low heating value (LHV) and higher carbon conversion efficiency.

References

[1] http://greenfuels.org/, Canadian Renewable Fuels Association.
[2] Y. Wang, C.M. Kinoshita, Sol Energy 49 (1992) 153–158.
[3] S. Turn, C. Kinoshita, Z. Zhang, D. Ishimura, J. Zhou, Int. J. Hydrogen Energy 23 (1998) 641–648.
[4] P.M. Lv, Z.H. Xiong, J. Chang, C.Z. Wu, Y. Chen, J.X. Zhu, Bioresour. Technol. 95 (2004) 95–101.
[5] C. Franco, F. Pinto, I. Gulyurtlu, I. Cabrita, Fuel 82 (2003) 835–842.
[6] I. Narvaez, A. Orio, M.P. Aznar, J. Corella, Ind. Eng. Chem. Res. 35 (1996) 2110–2120.
[7] D. Ferdous, A.K. Dalai, S.K. Bej, R.W. Thring, N.N. Bakhsi, Fuel Process. Technol. 70 (2001) 9–26.
[8] R. Xiao, B. Jin, H. Zhou, Z. Zhong, M. Zhang, Energy Convers. Manag. 48 (2007) 778–786.
[9] T. Hanaoka, S. Inoue, S. Uno, T. Ogi, T. Minowa, Bioresour. Technol. 28 (2005) 69–76.
[10] T. Valliyappan, D. Frdous, N.N. Bakhsi, A.K. Dalai, Top. Catal. 49 (2008) 59–67.
[11] A. Valero, S. Uson, Energy 31 (2006) 1643–1655.
[12] D. Ferdous, A.K. Dalai, S.K. Bej, R.W. Thring, Can. J. Chem. Eng. 79 (2001) 913–922.
[13] J. Manya, J. Sanchez, J. Abrego, A. Gonzalo, J. Arauzo, Fuel 85 (2006) 2027–2033.
[14] S. Rapagna, N. Jand, U.P. Fosocolo, Int. J. Hydrogen Energy 23 (1998) 551–557.
[15] S.T. Chaudhari, S.K. Bej, N.N. Bakhshi, A.K. Dalai, Energy Fuels 15 (2001) 736–742.
[16] A.P. Steynberg, H.G. Nel, Fuel 83 (2003) 765–770.
[17] W.F. DeGroot, G.N. Richards, Carbon 27 (1989) 247–252.
[18] C. Dupont, G. Biossonnet, J.M. Seiler, P. Gauthier, D. Schweich, Fuel 86 (2007) 32–40.
[19] C.M. Kinoshita, Y. Wang, P.K. Takahashi, Energy Sources 13 (1991) 361–368.

Steam Gasification Of Wheat Dried Distiller's Grains In A Fixed Bed Reactor System

Chirayu Soni, Terrance A. Fonstad, Ajay K. Dalai and Elizabeth Gusta

(This is the paper is a draft of a paper that will be submitted for publication as the 2nd paper associated with DDG Gasification. The first being Tavasoli et al. (2009) where the initial work on oxygen gasification is reported)

Introduction

Both Morey et al. (2006a and 2006b) give heating values for corn distillers' grain (DG) ranging from 7800 kJ/kg at 65% moisture to near 22,000 kJ/kg dry. Liu et al. (2002) gives similar values for wet distillers' grains (rice) in china of 6167 kJ/kg. McKendry (2002a) gives heating values for various woods and cereal straws ranging from 16,100 kJ/kg to 21,200 kJ/kg. Heating values for wheat, oats and barley are not well documented. Murlin et al. (1929) gives heat values for cereal grains from experiments where grains were burnt in pure oxygen and the heat given off measured and similar results are available from The Irish Farmers' Journal (2005) but no reference is given. These references give the heating value of wheat, oats and barley as 17,000 to 18,000 kJ/kg at 10 to 15% moisture content. Tavasoli et al. (2009) conducted experiments using wheat dried distillers grain (DDGS) and corn (DDGS) in a continuos flow fixed bed reactor. They showed that DDGS produced approximately 10,500 kJ/m^3 of gas and the total gas production was 0.4 m^3/kg of biomass using an oxygen-nitrogen gas mixture as the carrier gas.

The objective of this work is to investigate the effects of reaction time, reaction temperature, and steam/biomass (wt. /wt.) ratio on products yields, heating value of product gas, and its compositions in steam gasification of wheat DDGS in a fixed bed reactor system.

Additional work was completed to determine the effect of moisture content on the gasification process.

Characterization of wheat dried distilleries:

The elemental analysis of the biomass was carried out using an Elementar Vario EL III CHNS analyzer (Elementar Analysensysteme, Germany) and is presented in Table 1. The oxygen content was assumed to balance the rest.

Table 1 Elemental analysis of wheat dried distilleries

Element	Wt. %
C	45.1
H	7.0
N	5.1
S	0.3
O*	42.5

*: Calculated using different [100- (C+H+N+S)]

It is clear from the Table 1 that C and H constitute more than 50 wt. % of the biomass material.

System description

Experiments were performed at atmospheric pressure in a single stage fixed bed reactor system. The schematic diagram is shown in Fig.1. The reactor was made up of Inconel tubing having 10.5 mm ID and 500 mm length. The reactor had three pins welded inside to support the fixed bed with the help of quartz wool. The reactor was placed inside the split tube furnace (Applied Test Systems, Inc., USA) with a thermocouple located at the mid-length of the heating zone. The temperature of the reactor was monitored and controlled by a temperature controller system (Eurotherm models 2132, USA). Nitrogen as an inert carrier was supplied at the desired flow rate from a separate cylinder through a needle valve

and mass flow meter (Aalborg model GFM17), while water was injected into the reactor by a syringe pump (Kent Scientific, Genie Plus Model, USA) at the desired flow rate. A glass

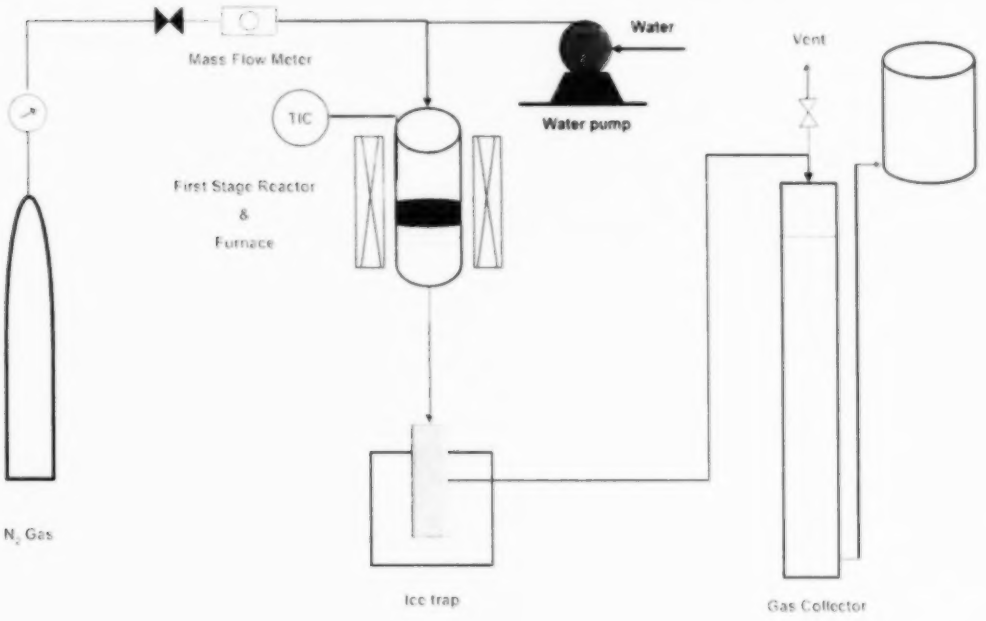


Fig. 1 Schematic diagram of experimental setup for steam gasification of wheat DDG in a single-stage fixed bed reaction system

condenser below the reactor, surrounded by a mixture of ice and salt, was used to condense the tar and cool down the product gases. The product gases were collected in the saturated brine solution column to prevent CO_2 dissolution in pure water. The brine solution column was further connected to the overhead surge tank to receive the displaced brine solution.

Experimental procedure

The feed material was placed inside the reactor. The material was supported on the plug of quartz wool, which was held on the supporting pins inside the reactor. The sample

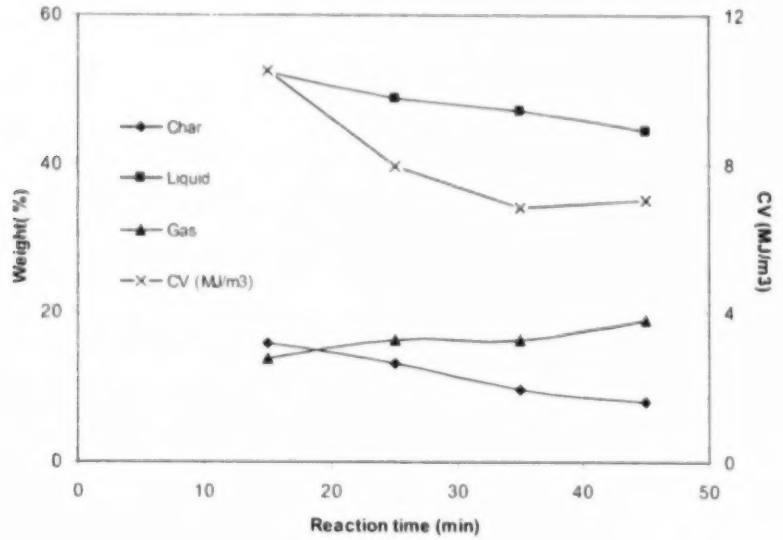
size of wheat DDGS was kept 0.75 g for all experiments. The heating rate of the first stage reactor was kept at 25 °C /min. Water injection was started when the reactor temperature reached 110 °C. It took approximately 27 to 35 min from 30 °C to reach the final temperature of 700 to 900 °C. After attaining the final desired temperature of the reactor, the reaction was allowed to continue for the desired reaction time. Subsequently the heating was stopped and the reactor allowed to cool down. The amount of product gases collected was measured by the displacement of the brine solution. They were analyzed using a gas chromatograph (Agilent 7890A). The amount of condensed liquid (tar + water) in the glass condenser and the char left inside the reactor were measured by a weight difference before and after the reaction. After each run, the reactor and glass condenser were cleaned using acetone and then dried with compressed air prior to the next run.

Results and discussion

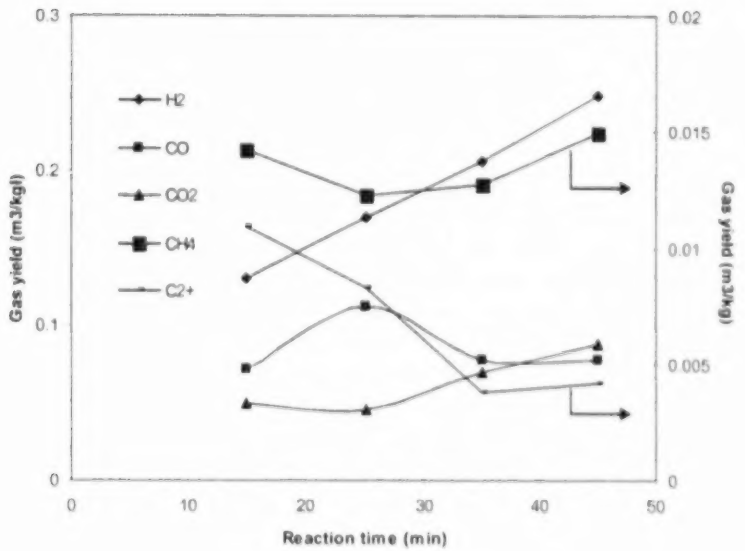
Effect of reaction time

The effects of reaction time were studied by keeping the reaction temperature at 850 °C, steam/ wheat DDGS (wt. /wt.) ratio at 0.5, and N_2 flow rate at 30 ml/min. Once the reactor temperature reached to 850 °C, the reaction was further allowed to continue for 15, 25, 35, and 45 min respectively in each run and the results obtained are presented in Fig. 2 (a) and (b). It was observed that char and liquid (tar + water) yields decreased from 16 to 8 wt. % and 52.4 to 44.4 wt. %, respectively while at the same time, gas yield improved from 13.9 to 18.9 wt. %. The trends observed signify substantial improvement in char gasification reaction with increasing the reaction time. The same could be witnessed by looking at H_2 and

CO yields. The H_2 and yields were increased from 0.13 to 0.25 m^3/kg biomass and 0.07 to 0.08 m3/kg biomass, respectively.



(a)



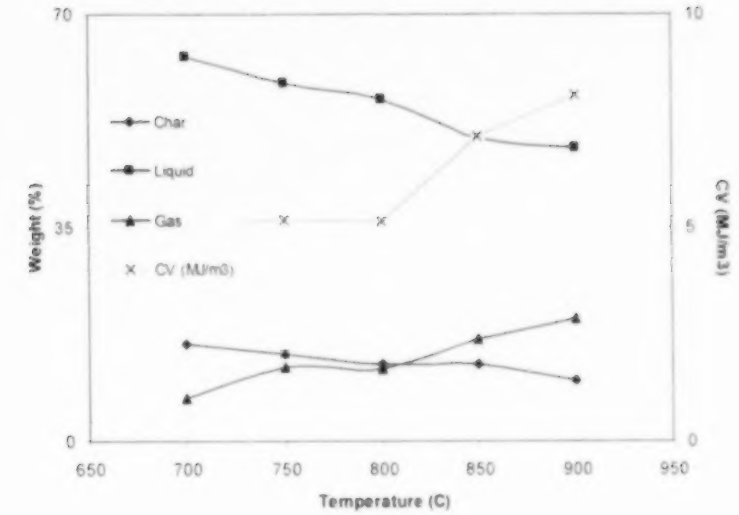
(b)

Fig. 2 Effects of reaction time on **(a)** products yields (wt. %) and heating value (MJ/m^3) **(b)** gas yields (m^3/kg biomass)

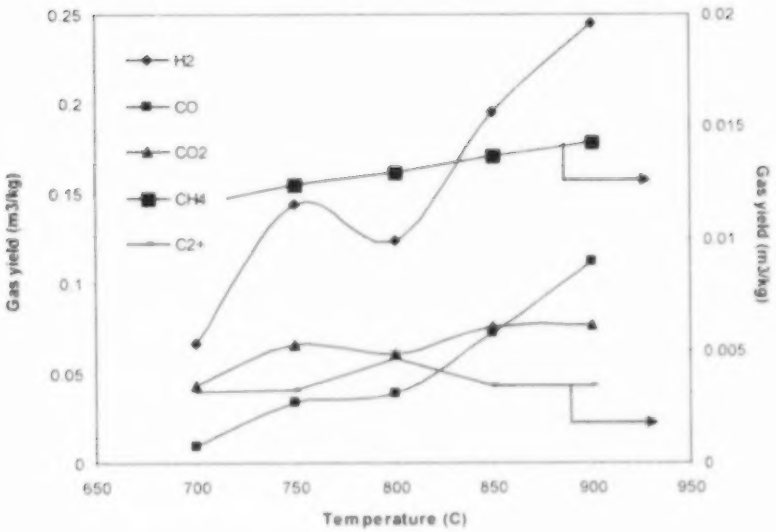
CO_2 yield also enhanced from 0.05 to 0.09 m^3/kg biomass while C_{2+} yield reduced from 0.01 to 0.004 m^3/kg biomass. This could be attributed to steam reforming reactions of tar and heavy hydrocarbons to produce H_2 and light hydrocarbons. The heating value of the product gas suffered from 10.5 to 7 MJ/m^3, which could be due to reduction in heavier hydrocarbons content.

Effects of reaction temperature

Gasification reactions are endothermic and favorable at high temperatures. Keeping this fact in mind, the reaction temperature was varied from 700 to 900 °C with increments of 50 °C while holding N_2 flow rate at 30 ml/min, steam/ wheat DDGS (wt. /wt.) ratio at 0.5, and the reaction time after attaining the final desired temperature at 25 min. The results are illustrated in Fig. 3 (a) and (b). Char and liquid yields declined from 16 to 9.8 wt. % and 63.1 to 48 wt. % with increasing the temperature and gas yield increased from 7 to 20.1 wt. %. Reaction of char with steam is endothermic and favorable at high temperatures. Moreover thermal cracking of liquid products are enhanced at higher temperatures, which can be noticed from a drop in liquid product yield and subsequent augmentation in gas yield. As a result, improvements in H_2 (0.07 to 0.25 m^3/kg), CO (0.009 to 0.11 m^3/kg), and CH_4 (0.01 to 0.014 m^3/kg) yields were obtained. In case of heavier hydrocarbons, no substantial variation was observed over the temperature range. The heating value of the product gas improved from 5.1 to 8.1 MJ/m^3, which is due to a large increase in H_2 and CH_4 contents. The effect of moisture content was determined using the same setup as Figure 1 with the exception of an additional furnace in series with the first, which allowed cracking of the gasses prior to cooling. Additionally, oxygen-nitrogen was the carrier gas used in these experiments.



(a)



(b)

Fig. 3 Effects of reaction temperature on **(a)** products yields (wt. %) and heating value (MJ/m^3) **(b)** gas yields (m^3/kg biomass)

Effect of Moisture Content

Figure 4 shows the impact of initial water content on the biomass conversion. Biomass conversion to gas increased from approximately 78% using dry DG and increased to approximately 90% when the initial moisture content was increased to 60%.

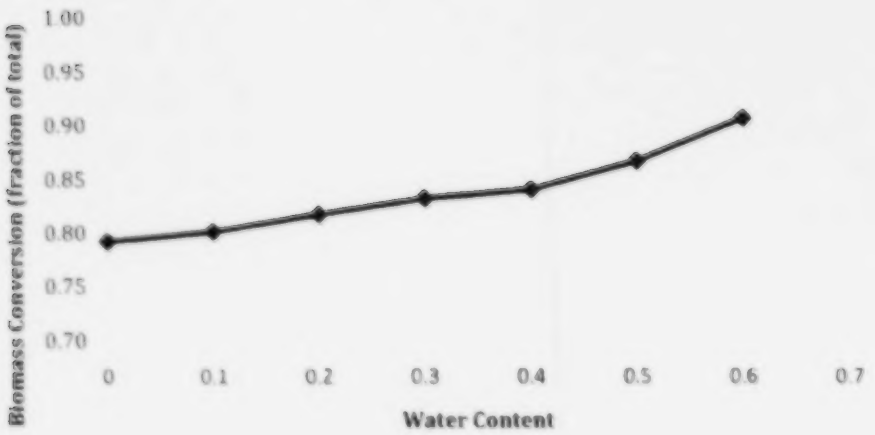


Fig. 4 Biomass conversion vs initial water content for gasification of wheat distiller's grain in a two stage gasification apparatus

Figure 5 shows the results of initial water content on the gas volume produced and the lower heating value (LHV) of the gas. As moisture content is increased from 0 to 60%, the gas volume produced increase three fold from approximately 1 L/g of biomass to 3 L/g of biomass. At the same time, the LHV of the produced gas declined approximately 30% from 30MJ/m^3 to 20MJ/m^3 when the moisture content was increased over the same range. It is interesting to note that the LHV of the gas did not decline appreciably until the initial

moisture content was above 20%. The reduction in LHV of the gas is a result of the change in gasses produced as the moisture content was increased. At 0% moisture content, the produced gas was approximately 6.4%, 6.4%, 42.9%, and 44.2% by volume hydrogen, carbon monoxide, methane and higher carbon gasses respectively. At 60% moisture content the produced gas consisted of 21.5%, 13.3%, 6.7%, 31.2% and 27.3% by volume hydrogen, carbon monoxide, carbon dioxide, methane and higher carbon gasses respectively.

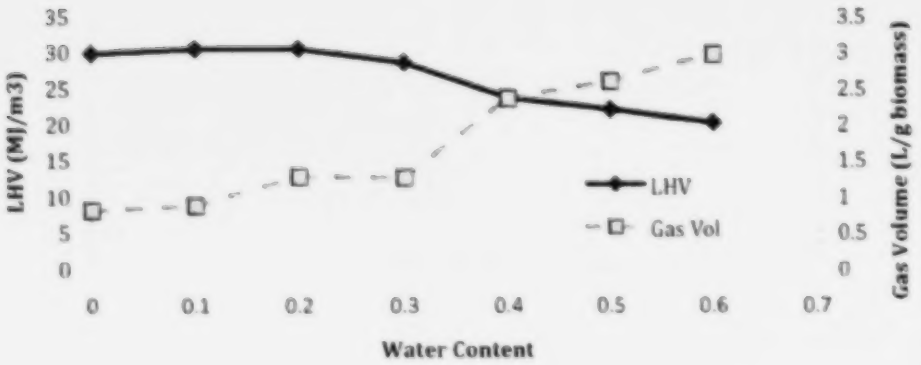


Fig. 5 Effects of water content on gas volume (L/g of biomass) and lower heating value of the produced gas (MJ/m^3)

Conclusions

From the above sets of experiments, it is concluded that wheat DDGS can be gasified using steam as a gasifying agent to produce syngas and a medium heating value product gas. It was also observed that longer reaction time allowed enhancement in char reaction to increase the H_2 yield, however the heating value of the product gas suffered at the same time. The reaction temperature had a profound effect from percentage increase in H_2 and syngas point of view. It also helped to better the heating value of product gas.

Moisture content increased gas volume three fold while the LHV decreased by 30% over the same range. This would appear to indicate that there is potential to gasify DG at relatively high moisture contents using moderate retention times and reactor temperatures near 800C to 900C.

References:

Liu, Y.-Z., Y.-C. Yuan and Y.-H. Chen, 2002. On the combustion mechanism and development of distillers' grain-fired boiler. Technical Note, Applied Thermal Engineering 22, 349-353.

McKendry, P., 2002a. Energy production from biomass (part 1): overview of biomass. Bioresource Technology 83. 37-46

Morey, R.V., D.G. Tiffany and D.L. Hatfield, 2006a. Biomass For Electricity And Process Heat At Ethanol Plants. Applied Engineering in Agriculture Vol. 22(5):723-728.

Morey, R.V., D.L. Hatfield, R. Sears, and D.G. Tiffany, 2006b. Characterization of Feed Streams and Emissions from Biomass Gasification/Combustion at Fuel Ethanol Plants. Paper Number: 064180, Presented at the 2006 ASABE Annual International Meeting, Oregon Convention Center, Portland, Oregon, July 9-12, 2006.13pp.

Tavasoli, A., M.G. Ahangari, C. Soni and A.K. Dalai. 2009. Production of hydrogen and syngas via gasification of the corn and wheat dry distiller grains (DDGS) in a fixed-bed micro reactor. Fuel Processing Technology 90 (2009), 472-482

The Irish Farmer's Journal, 2005. Cereals as a fuel. The Irish Farmer's Journal, May 28, 2005. http://www.farmersjournal.ie/2005/0528/farmmanagement/crops/feature.shtml

Abstract for a paper outlining the results of the DDG char as a soil amendment testing. To be presented at the Canadian Society of Soil Science Meeting, May 31 to June 4, 2010, Ottawa, Ontario

Biochars and ashes produced from pyrolysis and gasification as amendments to increase the fertility of a Brown Chernozem soil.

Khaled Alotaibi[1], Jeff Schoenau[1] and Terry Fonstad[2]

[1]Department of Soil Science, University of Saskatchewan and [2]Department of Agricultural and Bioresource Engineering, University of Saskatchewan

Pyrolysis and gasification of organic waste materials produces biochars and ashes as co-products of these processes. Pyrolysis is a low oxygen combustion process that produces carbon-rich chars from organic materials, whereas ash produced from gasification is typically high in phosphorus. Due to their content of nutrient, chars and ashes offer potential as alternative sources of fertilizer nutrient, and were examined in field and controlled environment experiments in 2009. The objective of the field experiment was to examine biochar applied alone at 2000 kg C ha^{-1} or combined with 50 kg N ha^{-1} as urea on canola yield, nutrient uptake and nutrient recovery on a nitrogen and phosphorus deficient Brown Chernozem. The objective of the growth chamber experiment was to examine the effect of two types of ash: dried distillers grain ash (DDGA) and meat & bone meal ash (MBMA) applied at 100 kg P ha^{-1} on canola yield and nutrient recovery on the same soil used in the field experiments. The field experiment treatments included: biochar (BC) applied alone, biochar with 50 kg N ha^{-1} (BC+N), 100 kg urea-N ha^{-1} and a control. In the growth chamber experiment the treatments were: 1 rate (100 kg P ha^{-1}) of DDGA and MBMA, 3 rates of mineral P (50, 100, 200 kg P ha^{-1}) as $Ca(H_2PO_4)_2$ and a control. All growth chamber treatments received a basal application of 200 kg N ha^{-1} as urea including the control. Biochar applied alone had limited effect on yield. However, BC+N showed equivalent yield to the urea treatment, despite having only half as much urea N added. This suggests that biochar may be improving nutrient retention and utilization. Both types of ash significantly increased yield similar to the mineral fertilizer treatment, and were deemed an effective source of phosphorus for canola nutrition.

Growth chamber pots growing canola using ordinary superphosphate compared to meat and bone meal ash (MBMA) and dried distiller's grain ash (DDGA)(wheat) were harvested the week of March 22 to 27, 2010 in the Soil Science Department at the University of Saskatchewan. Results shown in Figure 1 indicate MBMA and DDGA have significant potential as a crop phosphorus source with yields of 25% greater than the control and 17% less than those attained using ordinary superphosphate. Field trials are scheduled for summer 2010 under the direction of Dr. J.J. Schoenau.

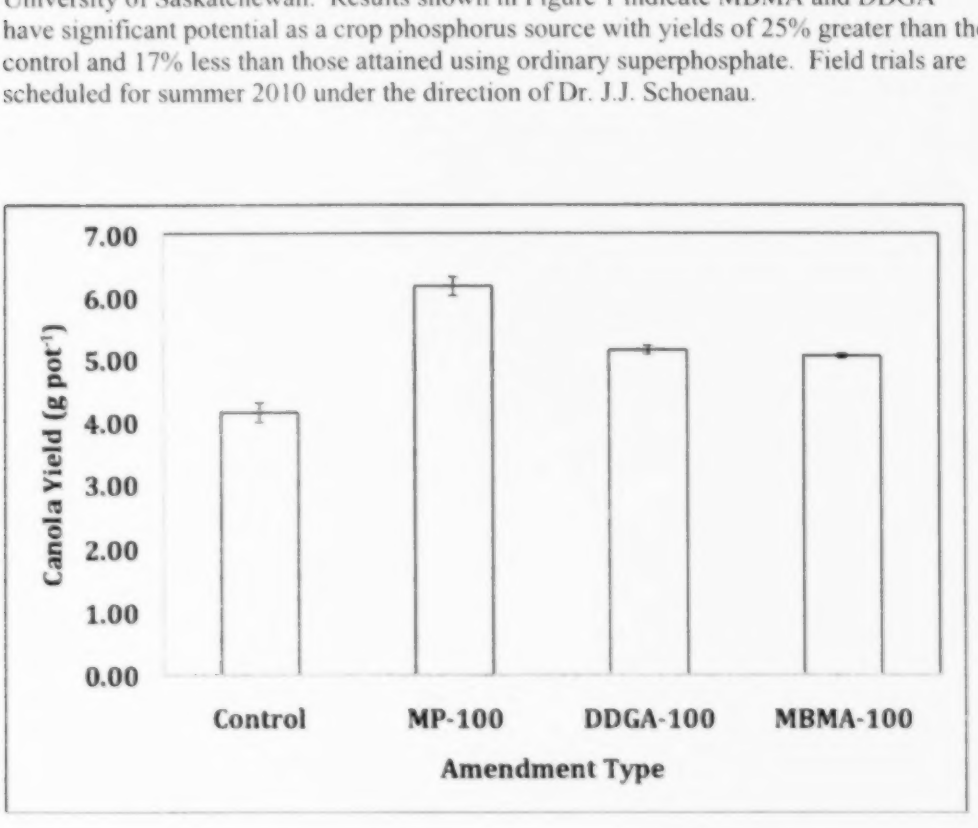


Figure 1: Response of canola biomass yield in growth chamber to addition of 100 kg P / ha as mineral P fertilizer (MP ordinary superphosphate), dried distillers grain ash (DDG), and meat-bone meal ash (MBMA).